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Comparative Economic Analysis of Uranium Oxide and Mixed Oxide fuel for VVER 1200 Nuclear Power Plant

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Abstract: A fundamental problem in most research aimed at assessing the economics of nuclear fuel cycles is to keep scenarios economically similar. A traditional method of doing this for Uranium Oxide (UOX) and Mixed Oxide (MOX) fuels is to evaluate both on the deterministic premise that the fuel will be transferred to geologic disposal once used. For cycles that use MOX fuel, this practice frequently results in greater costs. Geologic disposal is also not the only option for spent fuel from Light Water Reactors (LWRs). A combination of the uranium consumption profile, waste generation profile, nuclear services requirement profile, and a reactor usage profile are all related to each of the cycles. These timely streams of mass and related services comprise all of a cycle's cost information. From here, the most thorough way to analyze the various cycles economically is to compare their cost profiles for the same energy generation profile and same reactor type. This journal therefore investigated the cost of VVER fuel cycles in the face of back-end management concerns. In comparison to standard valuations, the framework establishes a major adjustment of the back-end expenses for countries employing MOX fuel option. However, in the reference situation, these reductions do not totally balance the higher recycling costs and cost of power generated from the nuclear power plant.

Keywords: Fuel Cycle, Uranium, Reactor, Nuclear Power Plant, Economic Analysis, Recycling.

1 Introduction

The nuclear industry saw a major transformation in 1980 with the development of mixed oxide fuel. Because of its benefits and applications in fast breeder reactors, mixed oxide fuel may eventually replace uranium oxide fuel, which has been the main fuel for nuclear reactors since their inception and is still in use today [1]. In a VVER-1200 reactor, the price differential between uranium oxide and mixed oxide fuel can fluctuate based on a number of variables, including market prices, material availability, and production methods. The waste product associated with uranium is starting to raise questions and requires further research. We are contrasting the economics of uranium oxide and mixed oxide fuel in order to ascertain which is more economical and effective and Economics is only one factor to consider when comparing fuel cycles, and it's not usually the most crucial one either. Other strategic considerations, such as energy security, safety, health, and technical advancement, also play a part in the sometimes contentious discussions around energy. This is especially true considering that the majority of energy costs are not accounted for by fuel charges [1]. It is desirable to make the economic conversation more comprehensive and to incorporate as many pertinent "strategic considerations" as possible into its meter because economics is one of the current modalities of debate and one that is relatively "transparent" to the general public. Among these is the interest in thermal recycling for future cycles, which this journal attempts to comprehend in some technical and economic details through the use of neutronics simulations and calculation methodologies [2]. By doing this, it makes an effort to bring up a fresh point of contention in the nearest future.

2 Literature Review

2.1 VVER-1200 Reactor

Pressurized, light water-cooled, and moderated, the VVER reactor was designed in Russia. It was made earlier than the 1970s and has been upgraded frequently. From generation I reactors to the newest generation III+ reactors, it now covers a broad spectrum of nuclear designs. Without a doubt, the development and expansion of the nuclear power

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industry in Russia and around the world was aided by VVER technology [3].

In 1964, the first VVER nuclear reactor was installed at the Novovoronezh nuclear power station. The VVER-210 and VVER-365 power reactors were the first two power reactors built on this location (the numbers originally referring to electrical output). The successful commissioning and operation of these early reactors paved the path for more efficient reactors to be built. The VVER-440 was the first VVER to be built in a serial format. For better heat retention [4].

The VVER-1200 is the most recent construction variant, and it is an upgrade of the VVER-1000 with a higher power output of approximately 1200 MWe (gross), improved plant performance, and more passive safety features [1]. One of the key aims of the VVER-1200 design was to lower costs while boosting safety without modifying the nuclear steam supply system's core architecture. Additional passive safety mechanisms were built to control mishaps that happened outside of the design foundation, and thermal power was boosted to 3200 MW [5].

The NPP-2006 project aims to improve customer appeal for dependability, maneuverability, and maintainability while also increasing safety, economic competitiveness, and consumer appeal for reliability, maneuverability, and maintainability. Primary and secondary circuit parameters have improved. Among the VVER-1200's putative safety benefits over other reactors are a passive decay heat removal system, a passive containment cooling system, and a passive hydrogen removal system [6].

The key principles that guided the design of VVER-1200 (NPP-2006) design are:

- Maximum use of proven technologies.
- Minimum cost and construction times.
- The balanced combination of active and passive safety protection systems, in general, to handle beyond design base accidents.
- Reduction in the influence of human factors on overall safety [3].

VVER-1200/NPP-2006 is divided into two plant design families. The V-392M variant, built by the Moscow Atomic Energy Project, is the first. The NvNPP II is a new-generation nuclear power station being built by JSC using the VVER1200 reactor plant, pursuant to the NPP-2006 project (V-392M design). St Petersburg Atomic Energy Project created the second family, the V-491 variant of the VVER-1200/NPP2006 project. The V-392M design, in contrast to the V-491 design, which depends heavily on active safety systems, makes excellent use of passive safety measures [3]. Chemically demineralized water with boric acid is utilized as a coolant and moderator in the primary circuit, with a fluctuating concentration of boric acid throughout operation, in the V-392M project, which has a 3200 MW thermal power and a 60-year vessel life. Water is heated to 328.9°C and supplied to the steam generator in each cooling loop, as shown in the Table. The VVER's steam generator is comparable in size to a VVER, but it has a distinct configuration: the VVER's cylinder is horizontal, whereas a PWR's cylinder is vertical.

Table 1: General VVER-1200 Parameters.

S/N	Parameter	Value
1.	Total power [MWt]	3200
2.	Net power plant efficiency [%]	34
3.	Normal primary coolant pressure [MPa]	16.2
4.	Primary coolant temperature at core inlet [°C]	289.2
5.	Primary coolant temperature at core outlet [°C]	328.9
6.	Service life [years]	60
7.	Average core power density [MW/m^3]	108.5
8.	Maximum enrichment of UO_2	4.95%
9.	Maximum fuel burn-up [MW-day/kgU]	70

In the steam generator, radioactive primary circuit water travels through 10978 heating tubes with a diameter of 16 mm, forcing secondary side water to boil. The cooled water returns to the reactor in the primary circuit at a temperature of 298.2°C. On the primary side, the main circulating pump circulates water. Each coolant loop may be separated using a valve. A steady pressure of 16.2 MPa is maintained by the pressurizer. The feedwater reaches the steam generator at 6.8 MPa and 227 °C, thanks to the primary water, which flows in tiny tubes at 328.9 °C. If the moisture content of the generated steam is not reduced, the turbine blades will be damaged. Moisture separator shutters are placed in the steam's route to accomplish this.

3 Methodologies

3.1 Getera-93 Programs

Several precise programs to calculate the neutron characteristics in a nuclear reactor cell have been created in recent years. These programs are usually based on the Monte Carlo method or represent a direct numerical solution of the gas-kinetic equation with a minimum of approximations [7]. However, such programs are not included in software packages that calculate the reactor as a whole, including solving dynamic and thermal-hydraulic problems. Programs that calculate neutron fields in groups are utilized for such jobs. This is a vast group of programs because each of them is configured for a specific class of reactor systems due to the multiple assumptions included in the algorithms of these programs. WIMS and GETERA are two programs of this type. The program is used to tackle problems such as small-group cross-section preparation for large-scale computations, investigations of various reactor features in cell and polycell models, fuel burn-up problems, and modeling of various reactor modes [8].

The method of probability of the first collisions is used to calculate the neutron-physical distribution of neutrons. In the slow-down region (10.5 MeV - 2.15 eV), the neutron flux density is calculated in the 22-group approximation based on the BNAB library. In the thermalization region (0.0 - 2.15 eV), the neutron spectrum is calculated using the Cadillac differential model using micro cross-sections obtained from the JNDL-2, ENDF-B4 nuclear libraries [9].

The GETERA software tool is meant to analyze energy circulation in the neutron space within reactor cells and poly cells using the first-collision-probability approximation, as well as numerous group approximations. The BNAB-93 nuclear-data library, which contains nuclear data for 135 nuclides in 299 energy bands, is used in the programme. The GETERA software is capable of doing fuel-deficiency calculations for a single fuel cell. And for a neutron-physical computation, the program GETERA is employed. The program is a code for calculating neutrons from one-dimensional cells and polycells of nuclear reactors in spherical, cylindrical, and planar geometries, both quickly and thermally.

4 Result Analyses and Discussion

4.1 Policy Impact of an Economic Approach

When comparing fuel cycles, economics is only one issue to examine, and it's not always the most important one: energy security, health, safety, technological edge, and other strategic concerns all play a role in the sometimes-polarized debates around energy. This is especially true given that fuel expenses only account for a small portion of total energy costs [10]. Because economics is one of the current modalities of debate, and one that is relatively "transparent" to the general public, it is desirable to make the economic discussion more comprehensive and to incorporate as many relevant "strategic considerations" as possible into its meter. The interest in thermal recycling for future cycles is one of these considerations, and this journal uses calculation techniques and neutronic simulations to try to understand some of its technical and economic aspects [2]. It attempts to introduce a new argument into the discussion by doing so.

Table 2: Sensitivity of the Cost to Natural Uranium and MOX Fuel Fabrication Cost.

S/N	INDICATOR	DESIGNATION	UNIT OF MESUREMENT	NPP WITH VVER (MOX)	NPP WITH VVER (UO_2)
1	Installed electric power	N_{EL}	MW	1200	1200
2	Efficiency (Gross)	η_{bp}	-	0.34	0.34
3	Coef. own needs		-	0.5	0.5
4	Fuel campaign		Year	2.4	2.7
5	Number of reloads	n	-	1	1
6	Initial enrichment by U235	X_H	%	0.0	4.69
7	Initial content of Pu	Z_H	%	7.5	0.0
8	Burnup	B	MW*day/kg	60	48
9	Amount of 235U in natural uranium	c	%	0.71	0.71
10	Amount of 235U in depleted uranium	y	%	0.2	0.2
11	Irretrievable losses of the i-th fuel cycle enterprise		-	0.01	0.01
12	The service life of the station	T_{CL}	Year	60	60
13	Price of natural uranium		$/kg	100	100
14	Unit price of division work		$/division	150	150
15	Cost for manufacture assemblies		$/kg	600	300
16	Average annual power utilization rate		-	0.9	0.9
17	Average percentage of deductions for renovation		% in a year	3.7	3.7
18	Specific investment		$/kW	1400	1400
19	Staff ratio		Personnel/MW el	0.5	0.5
20	Average annual salary fund		$/personnel year	14000	14000
21	Storage costs		$/kg	250	250

(Initial Enrichment of 235U – 4.4%).

4.2 Open Nuclear Fuel Cycle

Explanation of the technical calculations and plan for a nuclear power facility including a thermal reactor VVER-1200 Open cycles, in which fuel generated from raw ore passes through a reactor once and then proceeds straight to a final repository.

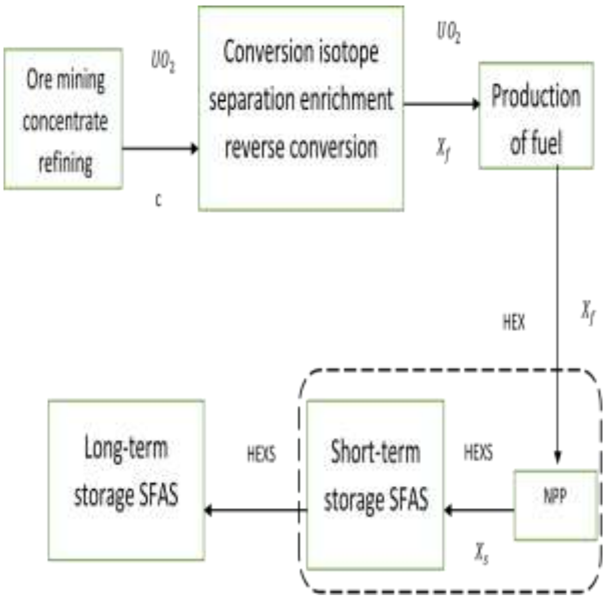

Fig. 1: Fuel cycle for a nuclear power plant with a planned reactor (VVER-1200)

Calculation of the Cost of Electricity Using Uranium Oxide (UO2) Fuel from Nuclear

Power Plant (VVER 1200)

Cost of electricity from NPP:

$$W_{EL} = N_{EL}(1-K_{CH})\varphi * 365 * 24 = 8.99 \cdot 10^6 \frac{MWhr}{year} \quad (1.1)$$

Amount of fuel needed per year:

$$G_X = \frac{N_{EL}*365\varphi}{B\,\eta^{br}} = 28.98\frac{t}{year} \quad (1.2)$$

Separation potential:

$$V(x_h) = (2*0.047-1)*\ln\frac{0.047}{1-0.047} = 2.81 \quad (1.3)$$

$$V(y) = (2y-1)*\ln\frac{y}{1-y} = 6.19 \quad (1.4)$$

$$V(c) = (2c-1)*\ln\frac{c}{1-c} = 4.87 \quad (1.5)$$

Specific work of separation:

$$n(x_h, y, c) = V(x_h) + (f(x_h, y, c) - 1)\cdot V(y) - f(x_h, y, c)\cdot V(c) = 7.47 \quad (1.6)$$

The price of enriched uranium up to 4.4%:

$$C_{4.7} = f(x_h, y, c)\cdot C_u + n(x_h, y, c)\cdot C_{dw} = 1944\,\frac{\$}{KG} \quad (1.7)$$

Required amount of natural uranium per year:

$$G_c = G_x \cdot f(x_h, y, c)\cdot (1+\varepsilon_i)^3 = 246\frac{t}{year} \quad (1.8)$$

Fuel component of the cost price:

$$C_T = \frac{1}{W_{el}}\left(C_U \cdot G_C + C_{4.7}\cdot G_x \cdot (1+\varepsilon_i)^2 + G_x \cdot C_{ma}\cdot (1+\varepsilon_i) + G_x \cdot C_{sp}\right) = 0.011\,\frac{\$}{kWhr} \quad (1.9)$$

Salary components:

$$C_{sc} = \frac{n_{sr}\cdot \Phi_{as}}{365\cdot 24\cdot \varphi} = 8.88\cdot 10^{-4}\,\frac{\$}{kWhr} \quad (2.0)$$

Depreciation component:

$$C_d = \frac{A_{ren}\cdot K_{sp}}{365\cdot 24\cdot \varphi} = 6.57\cdot 10^{-3}\,\frac{\$}{kWhr} \quad (2.1)$$

Cost of released energy:

$$C_e = 1{,}24\cdot(1{,}2\cdot C_T + 4\cdot C_d + 3{,}4\cdot C_{sc}) = 5.30\cdot 10^{-2}\,\frac{\$}{kWhr} \quad (2.2)$$

4.3 Closed nuclear fuel cycle

The closed fuel cycle is an advanced fuel cycle whose purpose is to achieve nuclear power sustainability by reducing the final waste's radiotoxicity and improving resource utilization while maintaining economic viability.

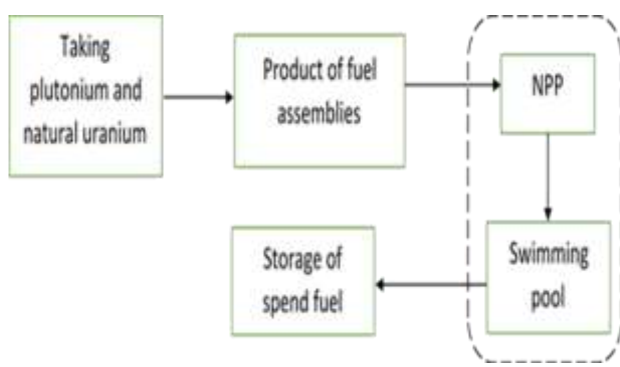

Fig.2: Fuel cycle for a Nuclear Power Plant with a planned reactor (VVER-1200).

Calculation on the cost of electricity using mixed oxide (MOX) fuel from nuclear power plant (VVER 1200)

Cost of electricity from NPP:

$$W_{EL} = N_{EL}(1 - K_{CH})\varphi * 365 * 24 = 8.99 \cdot 10^6 \frac{MWhr}{year}$$

Amount of fuel needed per year:

$$G_X = \frac{N_{EL} * 365\varphi}{B\,\eta^{br}} = 19.3 \frac{t}{year}$$

Initial fuel loading

$$G_o = G_x \cdot T_c = 52.2\ t \quad (3.13)$$

Full requirement

$$G_x^{tot} = G_0 + G_x\left(T_{st} - \frac{T_c}{n}\right) = 1159\ t \quad (3.14)$$

Required plutonium bought in a year:

$$G_z = G_x \cdot Z_b \cdot (1 + \varepsilon_i) = 1.1 \frac{t}{year} \quad (3.15)$$

Required natural uranium in a year:

$$G_u = G_x \cdot (1 - Z_b) \cdot (1 + \varepsilon_i)^2 = 18.6 \frac{t}{year} \quad (3.16)$$

Separation potential:

$$V(x_h) = (2 * 0.957 - 1) * \ln\frac{0.957}{1 - 0.957} = 2.65$$

$$V(y) = (2y - 1) * \ln\frac{y}{1 - y} = 6.19$$

$$V(c) = (2c - 1) * \ln\frac{c}{1 - c} = 4.87$$

Specific work of separation:

$$n(x_h, y, c) = V(x_h) + (f(x_h, y, c) - 1) \cdot V(y) - f(x_h, y, c) \cdot V(c) = 241.34$$

The price of enriched uranium up to 95%:

$$C_5 = f(x_h, y, c) \cdot C_u + n(x_h, y, c) \cdot C_{dw} = 54789.12 \frac{\$}{KG}$$

The price of plutonium:

$$b = C_5 \cdot (1 - Z_b) = 51704.49 \frac{\$}{KG} \quad (3.17)$$

Fuel component of the cost price:

$$C_T = \frac{1}{W_{el}}\left(C_U \cdot G_x \cdot (1 + \varepsilon_i)^3 + C_5 \cdot G_x \cdot (1 + \varepsilon_i)^2 + G_x \cdot C_{ma} \cdot (1 + \varepsilon_i) + b \cdot G_x + C_{sp}G_X\right) = 0.00837 \frac{\$}{kWhr} \quad (3.18)$$

Salary components:

$$C_{sc} = \frac{n_{sr} \cdot \Phi_{as}}{365 \cdot 24 \cdot \varphi} = 8.88 \cdot 10^{-4} \frac{\$}{kWhr}$$

Depreciation component:

$$C_d = \frac{A_{ren} \cdot K_{sp}}{365 \cdot 24 \cdot \varphi} = 6.57 \cdot 10^{-3} \frac{\$}{kWhr}$$

Cost of released energy:

$$C_e = 1{,}24 \cdot (1{,}2 \cdot C_T + 4 \cdot C_d + 3{,}4 \cdot C_{sc}) = 4.92 \cdot 10^{-2} \frac{\$}{kWhr}$$

Table 3: Economic Comparison of Uranium Oxide and Mixed Oxide fuel for VVER 1200

S/N	INDICATOR	SYMBOL	UNIT OF MESUREMENT	UO2	MOX
1.	Cost of electricity from NPP	ω_{el}	$\frac{MWhr}{year}$	$8.99 \cdot 10^6$	$8.99 \cdot 10^6$
2.	Amount of fuel needed per year	G_x	$\frac{t}{year}$	$2.898 \cdot 10^1$	$1.932 \cdot 10^1$
3.	Fuel component of the cost price	C_T	$\frac{\$}{kWhr}$	0.011	0.0084
4	Salary component	C_s	$\frac{\$}{kWhr}$	$8.88 \cdot 10^{-4}$	$8.88 \cdot 10^{-4}$
5.	Depreciation component	C_d	$\frac{\$}{kWhr}$	$6.57 \cdot 10^{-3}$	$6.57 \cdot 10^{-3}$
6.	Cost of produced energy	C_e	$\frac{\$}{kWhr}$	$5.30 \cdot 10^{-2}$	$4.92 \cdot 10^{-2}$

As shown in the table above, we can compare the differences in the cost of energy production and think of the best fuel to use for the fast bread reactor VVER-1200. The high cost of energy has been a major issue of concern in ensuring energy efficiency and in combating climate change, especially in developing countries. Hence, the need to explore and utilize the most cost-effective fuel for power generation.

5 Conclusions

In this study, the economic factor for both mixed oxide fuel and uranium oxide fuel is analyzed in an open cycle. With the result obtained, it shows that mixed oxide fuel can be of advantage considering sustainability issues. Mixed oxide fuel is very important because of the fissile concentration of the fuel and hence the burn-up can be increased easily by adding a bit more plutonium, whereas enriching uranium to higher levels of U-235 is relatively expensive. The most important is that mixed oxide fuel allows you to improve burn-up from 40 to 60 MWday/kg, keeping the same initial excess of reactivity. Unlike uranium oxide, the fuel cycle cost still decreases with fuel burn-up above the 60 MWd/kg. If the current reprocessing option is pursued, it is expected that global capacity for spent fuel storage will be sufficient for discharged volume over the next decade Therefore, economic improvement is reached by increasing fuel burn-up using the MOX fuel option and fuel reliability is satisfactorily achieved as compared to the Uranium fuel option.

Authors' Contributions

JD: Contributed to conceptualization, methodology, data curation, formal analysis, investigation, and wrote the original draft. SI: Provided conceptualization, methodology, data validation, and participated in reviewing and editing. SAO: Provided validation and contributed in reviewing and editing. KFA: Participated in formatting and editing the manuscript. All the authors read and approved the original draft.

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